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Bridging Sustainability and Chemistry Education: A Systematic Review of Problem-Based Learning in Green Chemistry for Enhancing Scientific Literacy

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Abstract: This study aims to identify models for developing teaching materials based on problem-based learning (PBL) in the context of green chemistry and to document the skills reported to have improved in these studies. In addition, this review examines how integrating PBL and green chemistry strengthens science culture, an area where research gaps persist, as previous results have not been systematically summarized. The method used in this study is a Systematic Literature Review (SLR) by following the PRISMA guidelines. Data are obtained from various scientific databases, including Scopus, SINTA, Web of Science (WoS), DOAJ, and Google Scholar, covering publications from 2022 to 2025. A total of 20 peer-reviewed articles that met the criteria were analyzed using a descriptive and bibliometric approach in VOSviewer. The results of the study show that most research reports an improvement in conceptual understanding, critical thinking skills, and environmental awareness when PBL is applied in the context of green chemistry. This approach helps students become aware of environmental issues through relevant problem-solving, such as energy efficiency and the use of environmentally friendly chemicals. The bibliometric analysis highlights five key themes: PBL, green chemistry, scientific literacy, local knowledge, and digital learning, pointing to a growing trend of integrating environmental, cultural, and technological perspectives in research. The thematic synthesis indicates that combining PBL with approaches such as SSI, context-based learning, or ethnoscience can further enhance scientific literacy. This review maps how PBL teaching materials are developed in Green Chemistry and how they relate to scientific literacy. The findings also emphasize the need for quantitative meta-analysis and longitudinal research to examine the long term effects of PBL, a gap not addressed in the 20 reviewed studies.

Keywords: systematic literature review, science literacy, green chemistry, problem-based learning.

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INTRODUCTION

Being scientifically literate means more than knowing science. It means being able to understand, evaluate, and apply knowledge about scientific methods and facts in everyday situations (Kumar et al., 2024). Regarding Indonesia's educational reforms, its disappointing PISA performance indicates that integrated scientific competence remains insufficient. There Is the need to foster understanding on higher order thinking (Sarkingobir & Bello, 2024). Indonesia's PISA 2023 rank for STEM competency is 71 out of 81. Indonesia's STEM performance in PISA 2022 was 383, and it did not meet the science competency benchmark. Many students face limited learning conditions, which do not allow mastery of the vital skills needed for science (Johansson et al., 2025). Innovative and contextual competency framework. There is a need to implement a more innovative, contextually relevant competency framework to reform learning processes and achieve more significant outcomes.

Outside the Indonesian context, concerns about low levels of scientific literacy reflect broader global challenges in science education. International literature consistently reports that students across various education systems find it challenging to apply scientific knowledge to real-world situations, particularly in sustainability, environmental decision-making, and sociological scientific reasoning (Goecke et al., 2026). Recent global studies emphasize that improving scientific knowledge requires a learning environment that goes beyond rote learning and prioritizes research, problem solving, and contextual learning experiences, in line with the skills needed in the 21st century (Kim & Liou, 2026). In this case, the challenges identified in Indonesia's PISA results reflect broader international trends, reinforcing the issue's relevance for a global audience.

Multiple global investigations advocate for improving the quality of science education, particularly by integrating 21st-century science education frameworks (Oliver & Adkins, 2020). Vaz et al. (2025) state that contemporary science literacy comprises three dimensions: functional, critical, and socio-cultural. It is used to address global sustainability challenges and to reference scientific insights. A systematic review and meta-analysis in science education further indicated that student-centered PBL pedagogy is closely associated with improvements in higher-order thinking, conceptual understanding, and scientific reasoning, which are very different from conventional learning (Miller et al., 2025). This must be based on learning activities with authentic problems.

With advances in education, more publications emphasize the importance of integrating sustainability into chemistry education. Green chemistry has often been proposed as a framework for linking chemical knowledge with environmental responsibility, ethical considerations, and social relevance (Clapson et al., 2025). An overview of green chemistry teaching shows that contextualizing chemical content through sustainability-oriented problems can improve student engagement and conceptual understanding (Widyantoro et al., 2025). However, existing reviews tend to treat PBL and green chemistry as separate areas, with limited summaries of how their integration specifically contributes to outcomes in science education.

More recent empirical studies have shown that combining PBL with Green Chemistry and ethnoscience through the application of chemistry learning in culturally relevant, environmentally based contexts (Ainur et al., 2025). Furthermore, an ethnoscience approach in strengthening chemistry literacy, along with local cultural integration and scientific concept comprehension. Wardani et al. (2024) also reported similar findings, noting that culture- and ethnoscience-oriented pedagogy enhances comprehension of abstract chemistry concepts.

In the context of this study, the development of Problem-Based Learning (PBL)- based teaching materials integrated with Green Chemistry principles is highly relevant (Yue et al., 2025). This approach not only emphasizes contextual problem-solving and critical thinking but also supports the development of sustainable science literacy aligned with socio-cultural values (Kuo, 2026). Therefore, this systematic literature review was conducted to identify the core components of effective learning arising from the application of PBL in the context of Green Chemistry and to improve students' science literacy, particularly in building meaningful, sustainability-oriented conceptual understanding.

Chemistry, one of the natural sciences, focuses on the properties, structures, and changes of different substances, along with the principles that underlie them (Mustansar et al., 2025). Learning chemistry involves three representative structures, in which macroscopic, sub microscopic, and symbolic components help learners conceptualize phenomena and scientific models (Lozano & Watson, 2021). Nevertheless, numerous studies indicate that students continue to struggle with literacy in chemistry, particularly in higher-order abstract topics and in chemical bonding and eco-friendly chemical reactions (Stekelenburg, 2026).

Given these circumstances, the PBL (Problem-Based Learning) method is validated to be effective in overcoming such challenges since it promotes the integration of real-life situations and the fostering of critical thinking, problem solving, and application of the concepts (Sarkingobir & Bello, 2024; Meiliati et al., 2026; Boelt et al., 2022). The application of Green Chemistry principles in the classroom is very helpful for students learning chemistry concepts. In this case, in particular, environmental problems such as waste reduction and the use of environmentally friendly materials are useful in sustainability (Anastas & Zimmerman, 2021).

International studies also show that a community-based, environmental, and sociocultural learning context can strengthen students' scientific skills. Highlights the potential of integrating local culture and ethnoscience into PBL-based chemistry teaching materials to improve conceptual understanding and sociocultural awareness (Çalik & Wiyarsi, 2025; Suwandi et al., 2025). However, existing studies and reviews generally examine these approaches separately and focus on the pedagogical effectiveness of PBL, the curricular relevance of green chemistry, or the role of ethnoscience in science education. To date, there is no systematic review of the literature that summarizes knowledge at the intersection of problem-based learning, green chemistry, and science education, particularly regarding how these elements can be implemented jointly in the development of teaching materials and evaluated using comparable learning outcomes. Furthermore, previous reviews rarely address methodological issues such as variations in problem design, contextual integration, and outcome measurement, thereby limiting the ability to draw sound, applicable conclusions. This gap highlights the need for a comprehensive and methodologically transparent synthesis, which is the objective of this study.

Students can learn science more holistically by applying the principles of green chemistry and integrating ethnoscience into Problem-Based Learning (PBL) (Rizki et al., 2022). Students can be more sensitive to the surrounding environment by applying modern scientific concepts, thereby maintaining a sustainable, healthy, and beneficial environment while integrating it with local culture (Mashami, 2025; Shavlik et al., 2022). 21st-century learning innovates in the development of PBL-based teaching materials that integrate the principles of Green Chemistry, enabling students to understand chemistry concepts in a meaningful way (Amoneit et al., 2024). This approach improves students' science literacy, making them more sensitive to environmental issues and enabling them to seek solutions related to sustainability, environmental problems, and social responsibility. This combination of approaches aligns with the Independent Curriculum, which emphasizes contextual learning through exploration of the environment.

Based on the above explanation, developing problem-based teaching materials that address green chemistry and ethnoscience can improve students' scientific competence across cognitive, affective, and socio-cultural domains. In addition, these teaching materials can add new learning experiences that are more relevant to sustainable living. More specifically, this review seeks to address the following research questions: RQ1. What are the characteristics of PBL-based instructional material design that incorporates green chemistry principles in chemistry education research for the period 2022-2025? RQ2. What contextual factors influence the variation in the effectiveness of interventions aimed at improving scientific literacy? QR3. What empirical and methodological gaps remain in research on green chemistry-based PBL, particularly with regard to dimensions of scientific literacy that have not been sufficiently explored?

METHOD

Research Design

This Systematic Literature Review (SLR) used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. It is guided by PRISMA because it provides a comprehensive framework, ensuring a more accurate, transparent, and methodologically strict review process. The clear structure and standards of PRISMA make for the systematic identification, assessment, and compilation of relevant studies. Therefore, the use of PRISMA in this study is very appropriate because it aligns with the research purpose, which is to assess the effectiveness of developing PBL-based teaching materials in green chemistry to improve students' knowledge literacy.

Search Strategy

Scopus, SINTA, Web of Science (WoS), DOAJ, and Google Scholar were selected to ensure comprehensive coverage of research on chemistry education. SINTA was included to collect nationally relevant studies on PBL and green chemistry that might not appear in international databases; to reduce heterogeneity in quality, only SINTA journals with an S2 rating or higher that confirmed they used formal peer review processes were considered. The search was conducted using structured search strings adapted to each database. Boolean operators and term variations were incorporated, for example: ("problem-based learning" OR "PBL") AND ("green chemistry") AND ("scientific literacy" OR "scientific competence"). Additional synonyms, such as "sustainable chemistry education" and "environmental chemistry," were used where relevant to increase the retrieval's sensitivity. The publication period (2022-2025) was chosen to focus on the most recent advances in sustainable and competency-based chemistry education, which have grown rapidly in the post-pandemic period.

To ensure the review included only high-quality and relevant empirical studies, predefined inclusion and exclusion criteria were applied. Studies were included if they (1) used quantitative, qualitative, or blended methods, (2) explicitly addressed problem-based learning and green chemistry in relation to scientific literacy, (3) reported an instructional design, defined operationally as a documented sequence of learning activities such as learning objectives, materials developed, PBL stages implemented, assessment procedures, and classroom intervention steps, (4) be published between 2022–2025, and (5) provided full access to the full text, including appendices or supplementary materials, where available. Exceptions were conceptual papers or reviews without empirical data that are not related to the core construction, and the absence of a complete text.

Exclusion criteria were applied to rule out conceptual or theoretical works, studies unrelated to the central constructs, and articles lacking methodological clarity. To reduce subjectivity, methodological clarity was assessed using a five-point checklist: (1) clear research objectives and questions, (2) transparent samples and participant information, (3) explicit description of the educational intervention or teaching design, (4) use of validated or well-explained data collection instruments, and (5) consistent and reproducible data analysis procedures. Studies that did not meet at least three of these five indicators were excluded from the review.

The screening stage was carried out in several steps to ensure objectivity and reduce bias. The first step was to remove duplicate records (n = 17) from the initial results, leaving 83 studies for initial screening. Furthermore, titles and abstracts were examined, and 43 studies did not meet the criteria. The remaining 40 full-text articles were assessed in detail, while 20 studies were excluded because they did not address methodological clarity. This yielded 20 empirical studies for the final synthesis. All references are managed using Zotero to maintain accuracy and avoid duplication. The PRISMA flow diagram summarizing the selection process is presented in Figure 1.

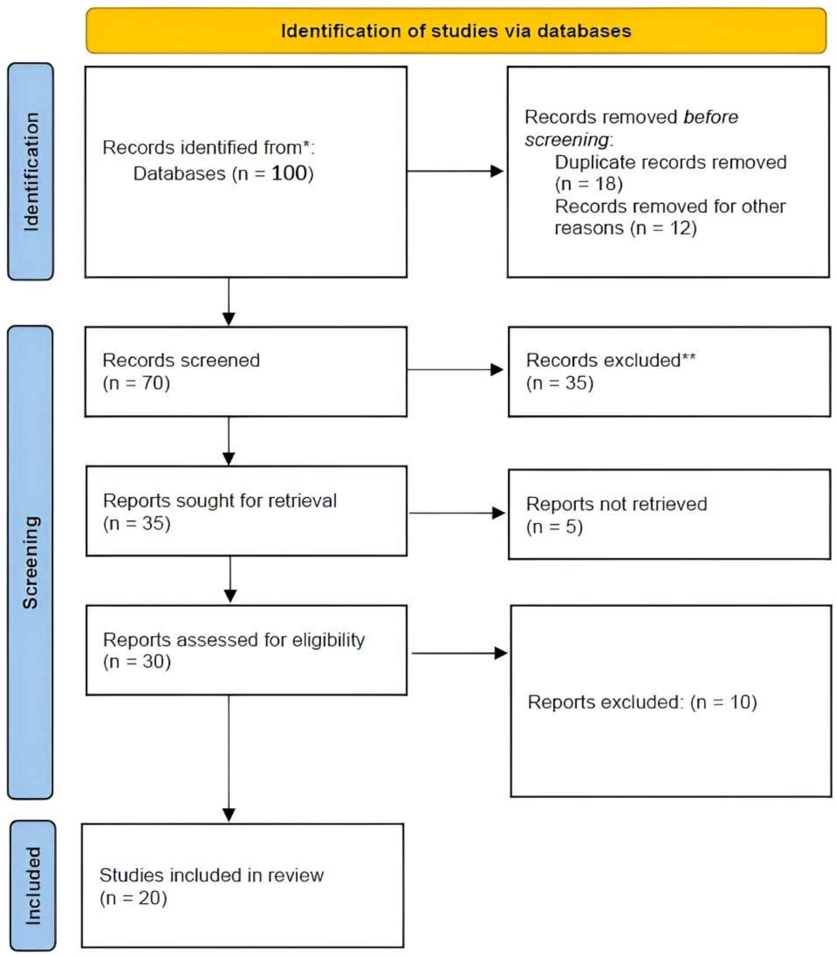

Figure 1. Article selection process using PRISMA flow diagram

Inclusion and Exclusion Criteria

Although the initial database search yielded 100 records, only 20 empirical studies were included in the final synthesis. This reduction was not the result of overly restrictive criteria, but rather a deliberate methodological decision to ensure analytical coherence and conceptual alignment with the objectives of this systematic review. Specifically, studies were included only if they simultaneously met three core criteria: (1) explicit implementation of Problem-Based Learning as the primary instructional approach,

(2) integration of Green Chemistry principles as substantive learning content rather than peripheral context, and (3) empirical measurement of scientific literacy outcomes.

Many studies identified in the initial search addressed PBL or Green Chemistry in isolation, focused solely on academic achievement without reference to scientific literacy, or adopted descriptive or conceptual designs without empirical data. Including such studies would have increased the quantity of articles but reduced the internal consistency and explanatory power of the synthesis. Therefore, the final selection of 20 studies reflects a balance between breadth and depth, prioritizing analytical rigor over numerical representativeness.

Data extraction was carried out in a structured manner using templates prepared to maintain accuracy, coherence, and methodological rigor. For each research selected, the information in it will be extracted, including the research design, the characteristics of the participants (for example, high school students or teachers), the learning context (problem-based learning combined with green chemistry), the development of teaching materials and strategies used, assessment instruments, and outcomes related to scientific literacy and environmental awareness of students. The extracted data is carefully cross-checked to minimize bias, and any discrepancies are resolved through team consensus.

In the next stage, a thematic analysis was conducted to integrate the findings and identify the main patterns across the reviewed studies. After the reading and repeating coding stage, the next stage is to group the compiled data into several main themes that demonstrate the application of problem-based learning in green chemistry to improve science literacy skills. Students are invited to deepen their conceptual understanding, conduct investigations, and think critically to develop a sustainable attitude. This coding stage focuses on several aspects: the development of material types (modules, digital media, and worksheets), pedagogical approaches such as PBL and inquiry-based learning, challenges in application during learning, and assessment quality (validity and suitability for higher-level thinking skills).

In the next stage, a reflective thematic analysis was conducted to integrate the results and identify the main patterns in the 20 studies reviewed. This approach followed the six steps described by Braun and Clarke (2006) using a deductive inductive strategy. The deductive approach was used because the initial themes were derived from the systematic review approach, namely the development of teaching materials based on PBL in the context of green chemistry to improve scientific literacy (as reported in many studies by Suwandi et al., 2025; Mashami & Pahriah, 2025; Çalik & Wiyarsi, 2025). On the other hand, the inductive approach was used to capture new topics emerging from the data, including the integration of ethnoscience, socioscientific issues (SSI), assessment challenges, and digital media trends.

The analysis process was carried out gradually. (1) two researchers familiarized themselves with the 20 articles by reading them thoroughly and summarizing the content of the studies, such as the type of teaching material (modules, worksheets, digital media), the pedagogical model (PBL, inquiry, SSI, ethnoscience), and learning outcomes (conceptual, critical thinking skills, scientific literacy, ecological awareness), according to the structure of the data in the archive; (2) the two researchers independently performed open coding on the first ten studies to generate initial codes relevant to the characteristics of the studies in the archive, such as PBL stages, green chemistry principles, assessment validity, and learning challenges. These codes were compiled into an initial codebook; (3) the codebook was tested in other studies and revised iteratively. Discrepancies in the coding process, such as differences in interpretation related to dimensions of scientific literacy (conceptual, socioscientific, affective) or the integration of locality (ethnoscience), were resolved through discussion until consensus was reached and, when necessary, clarified with a third researcher; (4) once the final code book was agreed upon, one researcher applied all codes to 20 studies, while another researcher cross checked 30% of the sample to ensure consistency and reduce bias; (5) similar or related codes are grouped into potential themes using axial coding, for example: development of teaching materials based on project-based learning, integration of green chemistry, integration of ethnoscience and SSI, quality of assessment, and results in scientific skills. Sixth, these themes are reviewed to ensure their internal cohesion and external relevance to the objectives of the SLR and the facts presented in the articles contained in the files. The final phase results in main themes that describe general patterns common to all studies, such as improving conceptual understanding, strengthening critical thinking, using local contexts, and emphasizing sustainability issues.

Data Analysis

Data analysis in this systematic literature review employed an integrated approach combining bibliometric analysis, descriptive quantitative analysis, qualitative meta-synthesis, and evidence gap mapping. Bibliometric analysis was conducted using VOSviewer to identify research trends and thematic relationships. Author keywords from the 20 included studies were used as the unit of analysis and were standardized by merging synonyms and removing non-informative terms. A full-counting method was applied with a minimum-occurrence threshold of 2 keywords, and co-occurrence networks were generated using association-strength normalization to identify thematic clusters. Descriptive quantitative analysis was performed to summarize key characteristics of the included studies, including research design, geographical distribution, educational level, type of PBL-based Green Chemistry intervention, and intervention duration. Frequencies and percentages were calculated to describe the overall research landscape and highlight underrepresented contexts.

A qualitative meta-synthesis was then conducted using a thematic synthesis approach to integrate findings across studies. Codes were compared and translated across studies to generate higher-order analytical themes related to the implementation of PBL in Green Chemistry and the dimensions of scientific literacy addressed. The evidence gap map was constructed based on information reported in article abstracts, author keywords, and methodological descriptions available in the selected studies. Finally, an evidence gap map was developed by cross-tabulating types of PBL-based interventions with the scientific literacy dimensions assessed, enabling the identification of research concentrations and gaps. This multi-layered analytical procedure ensured a systematic and transparent synthesis of the existing evidence.

The multi-layered analytical approach used in this study is designed not only to map trends in existing research but also to construct a more comprehensive conceptual framework. Bibliometric analysis examines the macro-level thematic structure of the field of study. In contrast, qualitative meta-synthesis identifies pedagogical models and learning mechanisms that emerge across various contexts. In addition, evidence gap mapping complements this by revealing areas of research that have already been extensively studied and those that remain unexplored, providing the basis for developing an integrative conceptual model of PBL Green Chemistry-Scientific Literacy.

RESULT AND DISCUSSION

Bibliometric analysis identifies several main groups that represent the relationships among research topics in chemistry education, especially those related to the application of PBL, green chemistry, and the improvement of scientific literacy skills. Each cluster has different characteristics depending on the research center and the terms that often appear in it. Identifying this cluster can clarify the direction of research and show the relationship among learning approaches, sociocultural contexts, and the use of technology to improve students' scientific literacy. Below are the results of a VOSviewer-based network visualization.

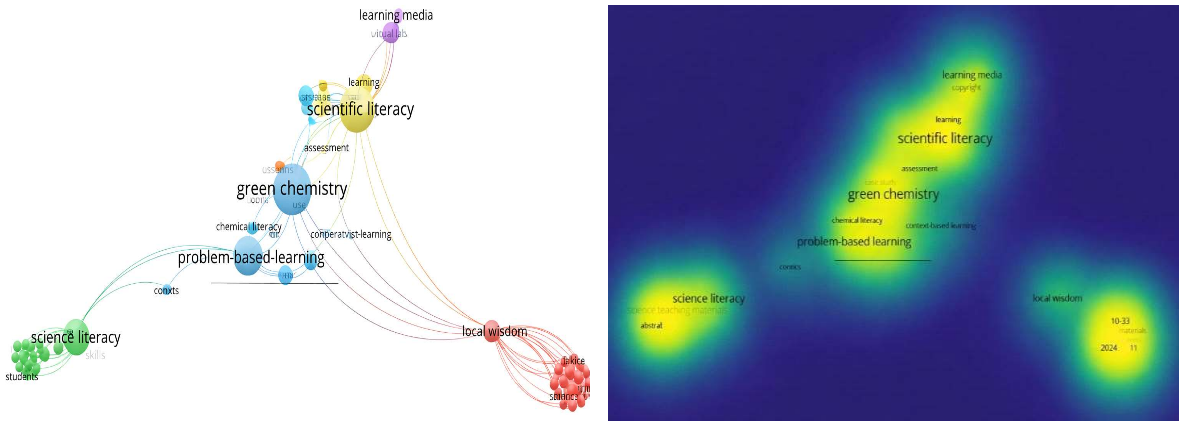

Figure 2. Network visualization results based on VOSviewer

Figure 2 displays the keyword co-occurrence network generated through VOSviewer analysis. The network's patterns and structure are described in the following section. This visualization illustrates the conceptual interconnections in recent research addressing PBL, Green Chemistry, and scientific literacy. One key finding is the central position of scientific literacy in the network, serving as a bridge between problem-based pedagogical approaches, sustainability-oriented chemistry content, and socio-cultural contexts such as local wisdom or ethnoscience.

The dominance of scientific literacy as a key node indicates that recent research increasingly positions it as a primary learning objective rather than a byproduct of mastery of the material. This pattern reflects a shift in the chemistry learning paradigm from a content-focused approach to competency-based learning, where PBL and Green Chemistry principles are strategically used to develop critical thinking, problem-solving, and environmental stewardship skills. The strong link between scientific literacy and local context also indicates that culturally and environmentally relevant issues play a crucial in role bridging learning approaches with meaningful literacy achievement.

The cluster connecting PBL and Green Chemistry demonstrates a well-established research focus on utilizing sustainability issues as a context for authentic problems. The proximity of this cluster to scientific literacy, compared to purely conceptual keywords, confirms that the research emphasizes the development of literacy competencies rather than conceptual understanding in isolation.

In contrast, the digital learning cluster occupies a relatively peripheral position within the network. This suggests that digital technology is still generally used as a supporting tool for learning and assessment, rather than as a primary driver of pedagogical innovation in PBL-based Green Chemistry education. The weak link between digital learning and the core cluster reveals a gap in existing research. It opens up opportunities for further research to explore the transformative role of technology in sustainability-oriented chemistry learning and scientific literacy. Based on these visualization results, a further analysis of each cluster was conducted to identify the elements, directions, and characteristics of the research, which are presented systematically in Table 1 below.

Table 1. Elements represented by each cluster

Cluster Color	Primary Keyword	Cluster Description
Blue	*Problem-based learning, green chemistry, chemical literacy, collaborative learning, case study*	The blue group represents the main focus of research on the development of problem-oriented learning integrated into the context of green chemistry. The terms in this group indicate a strong focus on improving students' critical thinking, collaboration, and problem-solving skills. Research in this group primarily examines how applying green chemistry principles can strengthen conceptual understanding and promote awareness of environmental sustainability through a contextual approach.
Yellow	*Scientific literacy, assessment, learning, context-based learning*	The yellow group focuses on learning outcomes and assessment related to improving scientific literacy. The use of the term "assessment" indicates that several studies have begun developing tools to assess students' scientific literacy. This group shows that scientific literacy is the main goal to be achieved through the application of PBL and green chemistry. Furthermore, the term "contextual learning" underscores the importance of learning that is relevant to real life to reinforce the transfer of scientific concepts.
Red	*Local wisdom, context-based learning, 2024, kearifan lokal*	The red cluster reflects a research trend that emphasizes integrating cultural values and local knowledge into science and chemistry education. The presence of concepts of local knowledge and context-based learning indicates that cultural context serves as a bridge to understanding scientific concepts, making learning more meaningful and rooted in students' social environment. This cluster also shows how ethnoscience can be used to strengthen ecological awareness and science competencies based on local culture.
Purple	*Learning media, articulate storyline, copyright, and digital learning*	The purple group includes research focused on innovation in digital teaching media in the context of PBL and green chemistry. The terms "storyline" and "copyright" refer to the use of interactive software and copyright issues in the development of digital teaching materials. In this group, they discussed the role of technology in increasing student participation, visualizing abstract concepts, and improving scientific literacy. However, its lesser relevance compared to the main group indicates that technological integration is only a supporting aspect, not a central one.
Green	*Science literacy, abstrak, penelitian, pengembangan bahan ajar IPA*	The green cluster contains a collection of research centered on the development of teaching materials for science and science education studies in general. The concept of education and teaching materials for science

	shows that this cluster emphasizes the development of learning tools to enhance scientific thinking skills and understanding of basic scientific concepts. The function of this cluster is to provide a conceptual foundation for other topics, serving as the basis for theory in the development of learning models, which are then enhanced by PBL and green chemistry.

The results of the analysis in Table 1 show that the blue and yellow groups are closely related to the development of PBL-oriented teaching materials and green chemistry. The red and green groups focus on integrating local knowledge and sociocultural relevance into science education. In contrast, the purple group focuses on new trends in using digital technology as a medium to support interactive learning. Based on the above statement, the pattern of relationships between these clusters indicates that science education is a crucial discussion that connects all of these approaches. There are several challenges in the 21st century, making applied chemistry learning must be more efficient and meaningful, so it is necessary to develop pedagogical innovations, cultural contexts, and the use of technology.

To complement the bibliometric results, a descriptive quantitative analysis was performed to summarize the methodological and contextual characteristics of the included studies. A deeper qualitative analysis of the methods sections of the 20 reviewed studies reveals substantial variation in how "problems" within PBL were conceptualized and implemented. Most studies (n = 13) employed semi-structured or ill-structured problems, typically grounded in real environmental contexts such as household chemical waste, water pollution, plastic degradation, or energy consumption. These problems were commonly framed as authentic cases drawn from students' local surroundings, aligning Green Chemistry principles with everyday experiences. In contrast, a smaller subset of studies (n = 7) relied on more structured or simulation-based problems, often presented through worksheets or digital modules with predefined solution pathways. Studies using real-world, ill-structured problems tended to emphasize student-led inquiry and argumentation, whereas more structured problems were primarily used to support conceptual clarification. This variation suggests that the nature of the problem design plays a critical role in shaping learning processes, yet it remains insufficiently theorized across the literature.

Quantitative Outcomes of PBL-Based Green Chemistry Interventions

Some studies report quantitative findings on scientific literacy and higher-order thinking skills. A formal meta-analysis could not be performed due to large differences in study design and variation in the outcome measures used. Therefore, a descriptive synthesis was performed by summarizing and comparing the effect sizes calculated from the available data.

Table 2. Individual effect sizes of PBL-Based green chemistry interventions on scientific literacy outcomes

Study	Level	Outcome Domain	Metric	Effect Size	Magnitude	Key Context
Mashami & Pahriah (2025)	Secondary	Scientific literacy	Cohen's *d*	0.78	Mod–Large	Ill-structured real-world problems
Suwandi et al. (2025)	Secondary	Conceptual & literacy	N-gain	0.62	Moderate	PBL module, Green Chemistry

Putri & Aznam (2024)	Secondary	HOTS literacy	Cohen's *d*	0.54	Moderate	Structured PBL module
Sudirman et al. (2025)	Secondary	Literacy & attitudes	Cohen's *d*	0.85	Large	PBL + ethnoscience
Çalik & Wiyarsi (2025)	Undergraduate	Socio-scientific reasoning	Cohen's *d*	0.47	Small-Mod	SSI-based PBL, short duration
Putri & Iriani (2025)	Secondary	Scientific literacy	N-gain	0.69	Moderate	Digital PBL module

Table 2 summarizes the effects reported in six empirical studies examining the impact of PBL-based green chemistry interventions on students' scientific knowledge. Although all six studies show positive effects, the magnitude of the effects ranges from moderate to significant, indicating that the interventions' effectiveness is influenced by differences in pedagogical design and methodological approaches.

An important factor explaining this variation is the design of the PBL problems. Studies reporting larger effects tend to have used poorly structured problems, characterized by open-ended questions, multiple solutions, and the requirement that students justify their decisions with scientific evidence. The design of such problems encourages in-depth inquiry, argumentation, and socio-scientific reasoning, which are essential elements of scientific culture. In contrast, studies with moderate effects tended to use more structured or guided problem-based learning formats, in which the learning stages and expected outcomes were predefined, potentially limiting deeper epistemic engagement.

Differences in effect size are also associated with the type of assessment instruments used. As shown in Table 2, studies that yielded larger effect sizes typically employed multidimensional science literacy instruments that captured cognitive, procedural, and affective components. In contrast, studies reporting smaller or moderate effects relied primarily on concept-focused performance tests or short-term posttests, which may underestimate gains in reasoning and socioscientific competencies fostered through PBL.

Furthermore, Table 2 indicates that interventions with explicit integration of ethnoscientific or socio-scientific issues (SSI) tend to report higher effect sizes than those in which green chemistry was primarily used as a context. Deeper integration of cultural practices or real-world environmental dilemmas appears to reinforce student engagement and facilitate meaningful knowledge transfer, thereby amplifying the observed impact.

Overall, the distribution of effect sizes in Table 2 indicates that the greatest advances in learning are associated with open-ended problem structures, comprehensive assessment approaches, and deeper contextual integration. In contrast, more modest advances are associated with structured problem designs and more limited measurement instruments. These findings suggest that variation in effect size reflects differences in methodological and instructional design choices rather than inconsistencies in the effectiveness of PBL-based green chemistry itself.

Descriptive and Visual Analysis

Figure 3 presents an Evidence Gap Map that highlights both concentrations and gaps in research on PBL-based Green Chemistry and scientific literacy. While most studies focus on conceptual understanding and general reasoning skills, the map reveals clear gaps in socio-scientific decision-making and environmental awareness, particularly in interventions that incorporate ethnoscience or local wisdom.

One of the main reasons for these gaps is the methodological difficulty of assessing higher-order and affective outcomes. Socio-scientific

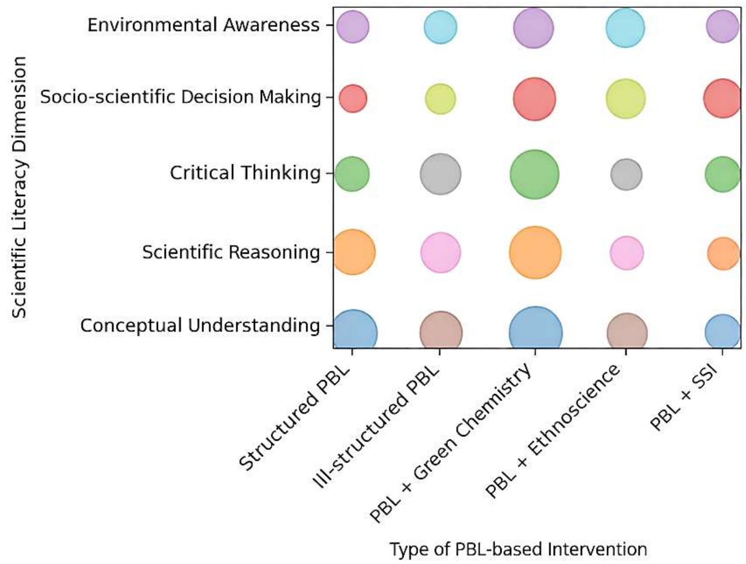

Figure 3. Evidence gap map of PBL-based green chemistry studies

decision-making involves ethical judgment, value-based reasoning, and trade-off evaluation, all of which are highly context-dependent and difficult to capture with standardized tools. As a result, researchers tend to prioritize outcomes that are easier to quantify, such as conceptual knowledge or problem-solving ability.

In line with this, the limited number of studies that specifically highlight environmental awareness may reflect theoretical uncertainty about this aspect's position within the framework of science literacy. In many studies in chemistry education, environmental awareness is often treated as an affective domain or a mere attitude, rather than as an inherent and essential component of science literacy. As a result, environmental awareness is more often reported descriptively or indirectly, rather than being systematically formulated and measured as a key learning outcome. This tendency is even more apparent in ethnoscience-based interventions, where cultural relevance is often emphasized. However, the explicit theoretical link to decision-making and environmental awareness is not always clearly developed.

Additional barriers include curriculum constraints and instructional feasibility. Designing PBL scenarios that simultaneously integrate Green Chemistry principles, ethnoscience knowledge, and sociological decision making requires substantial pedagogical expertise and sufficient instructional time. Teachers may face challenges balancing curriculum coverage with extended inquiry and discussion activities, are essential for developing higher-level literacy dimensions. These practical considerations may inhibit researchers from targeting more complex outcomes.

Despite these challenges, the gaps identified represent important opportunities for future research. First, future studies should prioritize the development and validation of robust assessment tools that capture socio-scientific decision-making and environmental awareness in culturally contextualized PBL settings. Second, research projects should move beyond short-term interventions toward longitudinal studies that examine how sustained engagement with green chemistry issues grounded in ethnoscience influences students' values, attitudes, and decision-making over time. Third, integrating digital learning environments, such as simulations or argumentation platforms, can support complex reasoning processes and make it more feasible to assess socio-scientific outcomes.

Overall, the Evidence Gap Map indicates that the research landscape remains dominated by cognitive achievement, while the affective dimension and higher-order thinking skills in science literacy have received little attention. Efforts to fill this gap are crucial to encourage the development of PBL-based green chemistry education towards a more holistic and transformative model, thereby equipping students to critically and responsibly address real environmental challenges.

Theme 1: Contextualization and Instructional Design as Key Mediators of PBL Effectiveness in Green Chemistry

Across the reviewed studies, the effectiveness of PBL in the context of Green Chemistry does not stem solely from adopting the PBL model. However, it is strongly mediated by the degree to which learning problems are contextualized and instructionally designed to reflect real environmental challenges. A consistent cross-study pattern indicates that PBL implementations grounded in authentic sustainability issues, such as waste reduction, environmentally friendly materials, and resource efficiency, are more successful in fostering students' scientific skills and critical thinking than decontextualized problem scenarios (Sarkingobir & Bello, 2024; Çalik & Wiyarsi, 2025). This suggests that contextualization serves as a central pedagogical mechanism that links inquiry-based learning with meaningful scientific engagement.

Rather than treating Green Chemistry as supplementary content, several studies demonstrate that positioning Green Chemistry principles as evaluative and decision-making criteria within PBL tasks enhances students' ability to connect scientific theory with real-world problem-solving. This is also in line with research by Anastas & Zimmerman (2021), which found that students learn to relate scientific theory to real-world experience in solving environmental problems, such as reducing waste and switching to environmentally friendly materials. PBL-based chemistry modules grounded in green chemistry principles can enhance students' conceptual understanding and ecological awareness (Suwandi et al., 2025; Sudirman et al., 2025; Putri & Aznam, 2024). This aligns with Dewi et al.'s (2021) research, which shows that continuous contextual learning strengthens the relationship between scientific knowledge and social values, making the learning process more meaningful and applicable.

An additional mediating factor consistently identified across studies is the integration of local cultural context through ethnoscience-based approaches. Embedding local knowledge and practices within Green Chemistry problems creates a cognitive bridge between abstract scientific concepts and students' everyday experiences (Wardani et al., 2024; Cahyani & Fadly, 2024). This contextual proximity increases relevance and engagement, thereby making learning more meaningful and applicable. However, the synthesis also reveals recurring challenges, particularly related to teachers' readiness to design complex, problem-based instructional materials and the limited availability of assessment instruments capable of measuring scientific competence holistically (Suwandi et al., 2025; Mashami & Pahriah, 2025). These constraints suggest that contextualized PBL design must be accompanied by aligned professional development and assessment strategies.

Based on the review of the analyzed articles, variations were found in the learning methods used to integrate green chemistry principles into the development of chemistry teaching materials. Although problem-based learning was the most commonly used method, several studies also combined it with other methods, such as socio-scientific issues (SSI), context-based learning, and ethnoscience. A comparison of these teaching methods is shown in Table 3 below.

Table 3. Distribution of instructional approaches used in green chemistry-oriented chemistry education

Researcher	Learning Approach	The Context of Green Chemistry	Focus on Learning Outcomes
Mashami & Pahriah (2025)	*Problem-Based Learning*	Experiments based on sustainable environmental issues	Improvement of science literacy and scientific analysis skills
(Suwandi et al., 2025; Sudirman et al., 2025, and Putri & Aznam, 2024)	PBL + *Etnoscience*	Green chemistry module with local cultural context	Strengthening conceptual understanding and ecological awareness
(Çalik, M., & Wiyarsi, 2025)	*Socio-Scientific Issues* (SSI)	Analysis of social and environmental issues in chemistry	Improvement in critical thinking and scientific argumentation skills
(Hisyam & Handayani, 2024)	*Context-Based Learning*	Social and cultural relevance in the concept of chemistry	Meaningful learning and improvement of contextual science literacy
(Cahyani & Fadly, 2024)	*Etnoscience Approach*	Environmentally friendly traditional practices	Integration of local wisdom and sustainability awareness

The results of the analysis in Table 3 show that the PBL model is the most dominant approach in the development of chemistry-based chemistry teaching materials, followed by the Socio-Scientific Issues (SSI), Context-Based Learning, and Ethnoscience approaches. The dominance of PBL signals a paradigm shift from teacher-centered to student-centered learning. PBL is effective in facilitating critical thinking and sustainable problem solving (Eichentopf & Dieter, 2025). Importantly, systematic evidence indicates that PBL adaptations incorporating structured scaffolding and reflective tasks consistently yield stronger outcomes in students' critical thinking orientation, underscoring the importance of instructional design quality rather than model selection alone.

The PBL model strengthens critical thinking and analytical skills, enabling students to understand and apply Green Chemistry principles in real-world situations (Suhaidah et al., 2020). This approach encourages students to engage more deeply with the learning material through complex, context-based problem-solving, helping to shape future professionals who are more resilient in facing the demands and challenges of the chemistry field (Vaz et al., 2025). PBL in Green Chemistry teaching can improve students' understanding of green chemistry concepts, and most students can identify and apply these concepts in a practical context, thus improving their conceptual understanding (Valderrama et al., 2023).

The integration of SSI and context-based learning within PBL frameworks further extends students' epistemic and socio-scientific competencies. SSI-based approaches, for instance, promote argumentation and ethical reflection by engaging students with scientific issues that carry social and moral implications (Priyanka & Selamat, 2021). Similarly, context-based learning allows students to relate chemical concepts to everyday life, making learning more meaningful and relevant (Sulistina. Ethnoscience-based integration complements these approaches by combining modern scientific knowledge with local wisdom, particularly in environmental conservation practices such as traditional waste management (Zidny et al., 2020; Krasnod, 2024). The integration of PBL, SSI, context-based learning, and ethnoscience can make learning more meaningful and efficient, as it not only involves theory but also improves students' science literacy skills related to local environmental problems (Yazid et al., 2020). Synthesized across studies, these approaches do not replace PBL, but rather function as contextual and epistemic extensions that broaden its impact on scientific literacy.

Overall, this thematic synthesis indicates that the development of PBL based teaching materials in Green Chemistry is most effective when guided by three interrelated design principles: (1) the use of authentic, sustainability driven problem contexts; (2) the operationalization of Green Chemistry principles as epistemic constraints within inquiry processes; and (3) the integration of socio-cultural context through SSI and ethnoscience. These principles suggest that students' scientific competence in the 21st century emerges not merely from exposure to innovative learning models but from the coherent alignment of pedagogy, sustainability content, and contextual relevance, thereby positioning PBL as a powerful vehicle for fostering scientific literacy oriented toward sustainable development.

Theme 2: Green Chemistry as a Multidimensional Catalyst for the Development of Scientific Literacy

Across the reviewed studies, the integration of Green Chemistry into chemistry education emerges not merely as a content enhancement but as a catalytic mechanism for fostering multidimensional scientific literacy. A consistent cross-study pattern indicates that Green Chemistry contexts enable students to connect abstract chemical concepts with real-world environmental sustainability issues, thereby strengthening both conceptual understanding and the ability to apply scientific knowledge in socially relevant situations (Anastas & Zimmerman, 2021). This chemistry learning encourages students to assess social and environmental influences through continuous learning, thereby developing a more relevant and practical understanding of science (Mashami et al., 2025).

Rather than improving scientific literacy in a unidimensional manner, the synthesized findings demonstrate that Green Chemistry learning activates multiple literacy dimensions simultaneously. Studies integrating environmental problem contexts report improvements in students' analytical and critical thinking skills, particularly when learning tasks require evaluation of social and environmental impacts alongside chemical processes (Çalik & Wiyarsi, 2025). Students will gain a conceptual understanding of chemical reactions and the ability to evaluate their relevance to daily life and human ecological responsibility through contextual experiments and discussions.

The synthesis further reveals that Green Chemistry learning contributes to the affective and socio-scientific dimensions of literacy, particularly when sustainability ideas are explicitly embedded in teaching materials. Empirical evidence indicates that integrating Green Chemistry principles into chemistry modules enhances students' environmental awareness, sense of responsibility, and social engagement (Suwandi et al., 2025; Sudirman et al., 2025; Putri & Aznam, 2024). Similar findings are reported by Hisyam & Handayani (2024), who show that education focused on green chemistry can improve students' ability to solve environmental problems they often encounter.

Importantly, the reviewed studies highlight the mediating role of local context and ethnoscience in strengthening the social and cultural dimensions of scientific literacy. The influence of ethnoscience on green chemistry learning plays an important role in improving social learning, and students can learn directly by associating science with local wisdom (Sudirman et al., 2025; Wardani et al., 2024). This integration not only enhances conceptual understanding but also cultivates scientific awareness and an ethical stance toward environmental preservation, reinforcing the view that literacy development is inseparable from socio-cultural context.

The results of the synthesis show that learning chemistry by integrating green chemistry principles not only increases conceptual knowledge but also fosters a sense of responsibility and environmental awareness, thereby training them to improve their social skills. Details on the aspects of literacy that improved in each study are shown in Table 4 below.

Table 4 shows that integrating Green Chemistry increases science literacy in multiple ways. The conceptual and social scientific

Table 4. Distribution of scientific literacy dimensions developed through green chemistry-based instruction

Researcher	Enhanced Dimensions of Scientific Literacy	Implementation Context	Key Findings
Mashami & Pahriah (2025)	General scientific literacy & ecological awareness	Environmental project-based learning	Students can analyze the impact of chemicals on ecosystems
Suwandi et al. (2025); Sudirman et al. (2025) and Putri & Aznam (2024)	Conceptual literacy & environmental care attitude	Green chemistry module	Increased understanding of sustainability principl and environmentally friendly behavior
Çalik, M., & Wiyarsi, (2025)	Social scientific literacy (SSI) & argumentation	Discussion of social issues in chemistry	Strengthening critical thinking skills and evidence-based argumentation
Dewi et al., (2021)	Contextual & reflective literacy	Social context-based learning	Improved ability to appl chemical concepts to rea problems
Sudirman et al., (2025)	Affective literacy & scientific cultural values	Ethnoscience integration	Growing ecological awareness through local wisdom

dimensions are the aspects most often developed (Mashami & Pahriah, 2025; Çalik & Wiyarsi, 2025), while the affective dimension and scientific culture are the focus of ethnoscience-based interventions (Sudirman et al., 2025). Thus, *Green Chemistry learning* not only strengthens scientific understanding but also builds attitudes, values, and environmental awareness that are integral to mastering modern science literacy (Fors et al., 2023).

To address the challenges of contemporary science education, several studies advocate the development of contextual and interactive teaching materials that explicitly integrate Green Chemistry with inquiry-oriented pedagogies. PBL is often identified as a mechanism for fostering higher-order thinking through authentic problem-solving, while SSI approaches connect chemical knowledge with ethical and environmental considerations (Permatasari & Aji, 2024). Green chemistry materials are highly relevant to apply because they emphasize environmentally friendly chemistry and encourage students to understand the application of chemical concepts in the context of environmental problems they encounter daily (Putri et al., 2025).

Synthesized across studies, these findings suggest that Green Chemistry supports scientific literacy development by functioning as an integrative context that links conceptual knowledge, socio-scientific reasoning, and affective engagement. Green Chemistry principles can be implemented across educational levels with varying degrees of complexity, offering a structured yet flexible foundation for literacy-oriented science learning (Pia et al., 2023; Mammino, 2025). Consequently, scientific literacy in Green Chemistry education should be understood not as a discrete learning outcome, but as an emergent, multidimensional construct shaped by the interaction of pedagogy, sustainability principles, and contextual relevance.

Theme 3: Conditions and Mechanisms Underpinning the Effectiveness of PBL in Green Chemistry Learning

Synthesized across the reviewed studies, the effectiveness of PBL in Green Chemistry learning is not attributable solely to the instructional model. However, it emerges from specific learning conditions and cognitive mechanisms activated during problem-solving processes (Mashami et al., 2025). A consistent pattern indicates that PBL is particularly effective in enhancing students' conceptual understanding of abstract chemical concepts when learning tasks are anchored in real-world environmental cases (Schütt et al., 2019). By engaging students as active problem solvers, PBL encourages the integration of macroscopic, submicroscopic, and symbolic representations of chemical phenomena, thereby strengthening conceptual coherence and transfer (Suwandi et al., 2025; Sudirman et al., 2025; Putri & Aznam, 2024).

Across studies, improvements in conceptual understanding are closely linked to the development of critical thinking processes, including analysis, evaluation, and reflection (Sireerat et al., 2025). PBL scenarios that require students to interpret environmental problems related to chemical substances motivate learners to generate ideas, examine theoretical explanations, and apply scientific reasoning to sustainability-oriented decision-making (Çalik & Wiyarsi, 2025; Schütt et al., 2019). This pattern suggests that PBL functions as a mechanism for transforming abstract chemical knowledge into actionable understanding through iterative inquiry and reflective reasoning.

Beyond cognitive outcomes, several studies highlight PBL's role in fostering scientific literacy practices, particularly argumentation and evidence-based reasoning. Research by Mashami & Pahriah (2025) shows that through PBL, students can apply the science literacy component, namely assessing the accuracy of information, so that they can ask scientific questions and string together arguments based on facts. Similar findings were reported by Hisyam & Handayani (2024), who found that PBL, when combined with the theme of green chemistry, can improve students' ability to assess the social and scientific aspects of environmental problems. These results reinforce the view that PBL effectiveness lies in its capacity to integrate cognitive and epistemic dimensions of learning.

The synthesis further reveals that PBL's effectiveness is significantly enhanced when combined with contextual and cultural mediators, particularly ethnoscience-based approaches. The application of PBL in the learning process will be more efficient when combined with an ethnoscience approach (Wardani et al., 2024; Sudirman et al., 2025). This is because students can relate scientific concepts of green chemistry to local wisdom to create a sustainable life (Fors et al., 2023). Thus, the application of the PBL model in green chemistry learning not only builds deep conceptual understanding but also fosters critical, collaborative, and reflective thinking skills that are essential for science learning in the era of sustainability (Araripe, 2024).

Previous research shows that positive results are obtained when PBL is applied to green chemistry materials. It consists of improved understanding of concepts, critical thinking skills, and scientific skills listed in Table 5 below.

Table 5. Learning outcome patterns associated with PBL implementation in green chemistry education

Researcher	Aspects Tested	Instrument/ Measurement Method	Key Results
Mashami & Pahriah (2025)	Conceptual understanding & critical thinking	Science literacy test & classroom observation	Significant improvement in scientific analysis and interpretation skills
Suwandi et al. (2025); Sudirman et al. (2025) and Putri & Aznam (2024)	Macro-submicro symbolic connections	Representation-based conceptual tests	Students are able to connect the concepts of green chemistry thoroughly
Çalik, M., & Wiyarsi, (2025)	Scientific argumentation & reflective thinking	Analysis of SSI arguments	Improved skills in crafting scientific evidence-based arguments
Hisyam & Handayani, (2024)	Collaboration and problem solving	Observation of PBL activities	Students are more active, critical, and able to develop alternative solutions
(Wardani et al., 2024)	Integration of knowledge and cultural values	Authentic ethnoscience assessment	Learning is more contextual and socially meaningful

The outcome patterns associated with these mechanisms are summarized in Table 5, which shows that PBL's effectiveness in Green Chemistry learning manifests across three interrelated domains: cognitive understanding, higher-order thinking skills, and social-affective awareness. At the same time, most studies report significant gains in conceptual analysis and critical thinking (Çalik & Wiyarsi, 2025). Most studies show significant improvements in students' conceptual analysis and critical thinking skills (Oliveira et al., 2024). PBL will be more effective if meaningful learning is applied, combining local wisdom with environmental issues to consistently enhance affective and social aspects (Wardani et al., 2024). This distribution suggests that variations in instructional design and contextual emphasis shape the specific learning outcomes achieved through PBL.

Overall, this thematic synthesis indicates that PBL is most effective in Green Chemistry learning when it is implemented as a context-rich, inquiry-driven, and culturally responsive pedagogy. It can be seen that the goal of 21st-century education, which is to develop scientific skills, can be achieved by applying the PBL model to the material in the context of Green Chemistry.

Interpreting Variations and Contradictions Across Studies

Although a positive trend in the relationship is generally observed, several studies yield inconsistent results. Some learning activities show only limited improvement in the affective aspect of scientific literacy, especially in attitudes toward the environment, although students' understanding of concepts has improved. These differences in results are believed to be related to the intervention's relative brevity, the lack of space for student reflection, and the suboptimal role of teachers in facilitating the research process. In addition, studies conducted in resource- and infrastructure-constrained contexts report difficulties in implementing the PBL model openly, mainly due to time constraints and limited access to laboratory facilities, leading to a more teacherdirected learning approach. These findings confirm that the success of PBL-based Green Chemistry learning is strongly influenced by contextual factors, including teacher competence, institutional support, and student preparedness.

Theoretical Implications and Integrative Conceptual Model

In addition to highlighting the importance of applying Problem-Based Learning and Green Chemistry, this study also makes a theoretical contribution by proposing an integrative learning model that combines three main components: (1) the problem-based learning framework, (2) the principles of Green Chemistry, and (3) the social and cultural context, including the ethno-science approach and socio-scientific issues. Based on constructivist learning theory, the synthesis results show that knowledge formation is most optimal when students actively participate in solving open-ended problems relevant to real contexts. According to contextual learning theory, integrating local and cultural environmental issues is closely related to abstract concepts in chemistry and to everyday life experiences. The proposed model asserts that strengthening scientific literacy will occur optimally if cognitive, socio-scientific, and affective aspects are developed in an integrated manner through context-rich problems.

This synthesis has several concrete practical implications. For curriculum developers, the topic of "green chemistry" should be integrated into PBL units that explicitly incorporate real-world environmental issues relevant to the local context of the students. For teachers, professional development should go beyond procedural PBL steps and focus on designing unstructured problems, moderating student discussions, and integrating reflective assessment strategies. For policymakers, these findings underscore the need for flexible curricula, longer learning processes, and support for context-based learning materials that align sustainability goals with science education outcomes.

CONCLUSION

This systematic literature review examined how Problem-Based Learning (PBL) has been applied in Green Chemistry education and how this approach has been linked to different dimensions of students' scientific literacy. Rather than presenting a simple claim of effectiveness, the findings point to a recurring pattern across the reviewed studies: PBL-oriented Green Chemistry teaching materials are commonly associated with learning environments that support conceptual understanding, critical engagement with real-world environmental problems, and the development of sustainability-related awareness. At a broader level, these findings highlight the educational significance of connecting chemistry content with authentic ecological contexts. This issue has been widely advocated but only partially synthesized in earlier research. By systematically integrating bibliometric analysis, thematic synthesis, and evidence gap mapping, this review makes a distinct contribution to the field by clarifying how recent empirical studies have operationalized the relationship between PBL, Green Chemistry, and scientific literacy, thereby addressing a fragmentation gap identified in previous literature.

The implications of this review extend to both theory and practice in science education. Theoretically, the synthesis supports perspectives that frame scientific literacy as a multidimensional construct encompassing cognitive, socio-scientific, and affective elements, and positions PBL as a pedagogical approach capable of linking these dimensions within sustainability-oriented chemistry learning. Practically, the findings suggest that teacher education and professional development should place greater emphasis on designing context-rich Green Chemistry problems, facilitating inquiry-based discussions, and using assessment strategies that capture higher-order thinking and literacy outcomes. Nevertheless, this review is constrained by several limitations, including variation in research designs, short intervention periods, and limited use of comparable outcome measures across studies. These constraints limit the strength of cross-study generalization and point to important directions for future research. Longitudinal studies are needed to examine the persistence of scientific literacy development over time, while meta-analytic research would allow for more precise estimation of effect patterns across studies. Together, such approaches represent logical next steps for strengthening the empirical and theoretical foundations of PBL-based Green Chemistry education.

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